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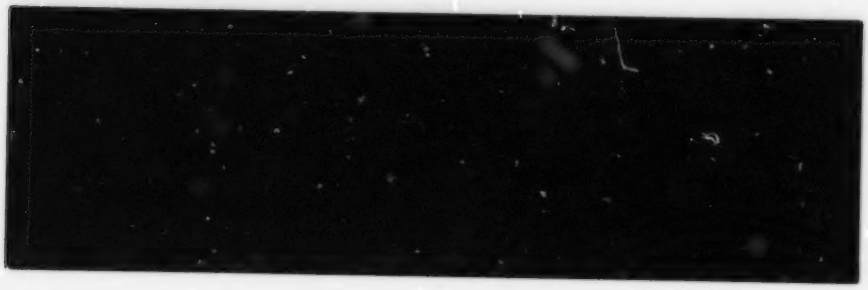

Canada

DEVELOPMENT OF ARTIFICIAL SILL PILLAR DESIGN, LUPIN MINE, NORTHWEST TERRITORIES
PART 2: PRE-MINING GROUND STRESS DETERMINATIONS

B. ARJANG

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B. Arjang*

ABSTRACT

The Echo Bay Mines Ltd. Lupin operation in Northwest Territories produces gold from a steeply dipping orebody by sub-level longhole open stope mining, leaving sill pillars in the ore. To increase ore recovery, a joint research project has been established to design and develop guidelines for artificial sill pillars. To provide background information for stability evaluations, pre-mining ground stress determinations were conducted on the 410 m and 890 m levels of the mine.

Ground stress determination from overcoring strain relief measurements indicates that, generally, the maximum principal compressive stress is horizontal in a NE/SW direction, and the intermediate principal compressive stress is sub-horizontal prevailing in a NW/SE direction. The minimum principal compressive stress is sub-vertical with varying direction. Stress gradients for maximum, intermediate and minimum principal compressive stresses vary, ranging from 0.0430 to 0.0693 MPa/m, 0.0271 to 0.0505 MPa/m, and 0.0127 to 0.0397 MPa/m, respectively. A comparison of average stress gradients, however, suggests that the Lupin Mine data follow the trend established from underground stress determinations in the Canadian Shield

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Key words: Sub-arctic; Pillar design; Ground stress determination.

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MISE AU POINT DE PILIERS DE SOLE ARTIFICIELS, MINE LUPIN, TERRITOIRES DU NORD-OUEST
PARTIE 2: CALCUL DES CONTRAINTES DU TERRAIN AVANT L'EXPLOITATION

B. Arjang*

RÉSUMÉ

L'exploitation Lupin de l'Echo Bay Mines Ltd. dans les Territoires du Nord-Ouest produit de l'or à partir d'un corps minéralisé à fort pendage, en exploitant des sous-niveaux en chambres vides par trous profonds, ce qui laisse des piliers de sole dans le minerai. Dans le but de récupérer plus de minerai, un projet de recherche conjoint a été mis sur pied pour élaborer des lignes directrices relatives aux piliers de sole artificiels. Pour constituer une base d'information destinée aux évaluations de la stabilité, les contraintes du terrain ont été calculées avant l'exploitation, aux niveaux 410 et 890 m de la mine.

Le calcul des contraintes du terrain à partir de mesures de relaxation des déformations par surcarottage indique que la contrainte de compression principale est en général maximale à l'horizontale en direction NE/SW, intermédiaire dans un plan subhorizontal en direction NW/SE, et minimale dans un plan subvertical et une direction variable. Les gradients des contraintes de compression principales maximale, intermédiaire et minimale varient respectivement entre 0,0430 et 0,0693 MPa/m, 0,0271 et 0,0505 MPa/m, et 0,0127 et 0,0397 MPa/m. La comparaison des gradients moyens des contraintes indique toutefois que les données de la mine Lupin suivent la tendance établie à partir des calculs des contraintes souterraines dans le Bouclier canadien.

Mots clés: sub-arctique; construction des piliers; calcul des contraintes du terrain.

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INTRODUCTION

The Echo Bay Mines Ltd. Lupin operation produces ore from a steeply dipping orebody by a sub-level longhole open stope mining method, leaving sill pillars in the ore. To increase the ore recovery, in a joint research project between Echo Bay Mines Ltd. and CANMET, design criteria for establishing artificial sill pillars with waste rock will be developed. With increasing productivity, the objective is to achieve ground stability and mine safety without leaving horizontal sill pillars in the ore.

Major elements of the research project are:

1. Rock mechanics investigations to determine in situ stresses and physical properties of various rock types, and instrumentation to monitor ground movements around the proposed test site excavations;
2. Based on rock mechanics data, to modify a numerical model of the mine and develop design guidelines for artificial sill pillars.

As part of the project, pre-mining ground stresses were determined on the 410 and 890 levels, 410 m and 890 m below surface. Overcoring strain relief measurements were conducted in the hanging wall, footwall and orebody in the west zone of the mine. Rock properties were tested on core specimens obtained from the stress determination sites.

GEOLOGICAL SETTING AND MINING BACKGROUND

The Lupin Mine is located some 400 km northeast of Yellowknife and 100 km south of the Arctic Circle in the Northwest Territories as shown in Figure 1. The Lupin deposit occurs in amphibolite iron formation confined by rock units of phyllite/siliceous phyllite and quartzite/metagreywacke with well defined contacts. It is folded and tilted into a megascopic antiform-synform-antiform structure (1). The gold-bearing iron formation is a Z-shaped structure made up of steeply dipping ore zones: the west, central and east zones. The ore zones plunge at an angle of about 65°. A typical plan view of

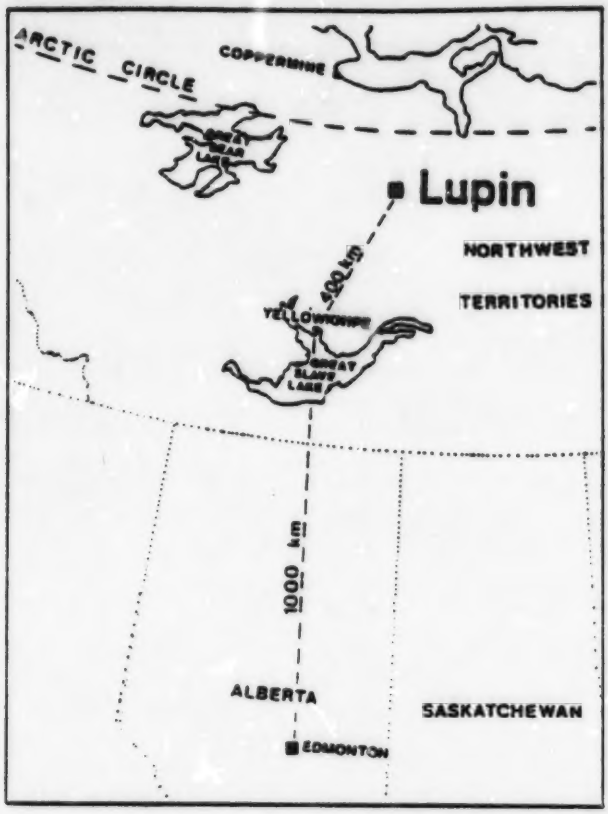

Fig. 1 - Location of Lupin Mine, N.W.T.

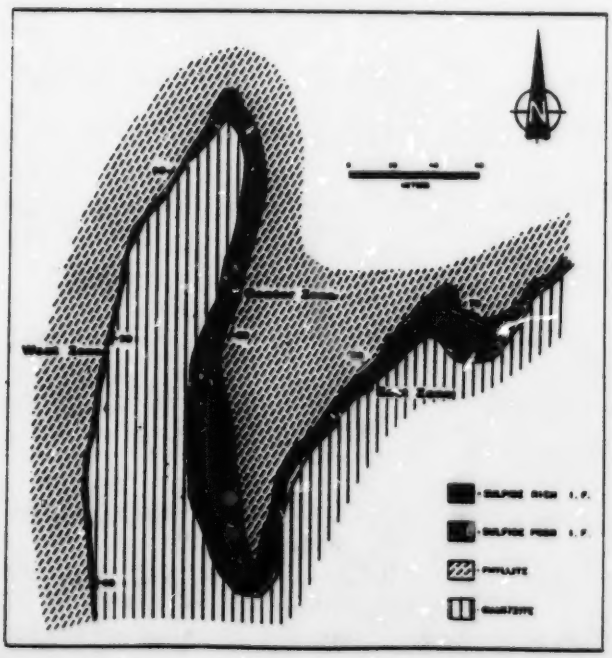

Fig. 2 - Typical plane view of Lupin Mine ore zones (1).

the ore zones and the structural setting is shown in Figure 2. The ore zones structure extends for over 600 m on strike and are presently confirmed to a depth of about 1000 m below surface. The centre zone is the widest and varies from 4.5 to 20 m, and the west zone is an average 1.5 m wide.

No significant displacement of the ore zone is known as a result of faulting. Limited structural analysis indicates two dominant steeply dipping joint sets in NNE and easterly directions.

The present mining method is sub-level longhole open stoping in all three ore zones. The steeply dipping orebody and competent hanging wall and footwall rocks permit use of this mining method, as openings will stand without support over considerable spans. Pillars are left for support where unfavourable ground conditions exist. This method has been used to a depth of 570 m. However, at greater depths, a modified mining method will be employed to control anticipated ground problems (1). The permafrost extends to a depth of about 500 m below surface.

Mine levels are established at 80 m intervals with sub-levels driven on strike in 20 m vertical intervals. The ore recovery is by haulage drifts and drawpoint accesses in the quartzite member. Longitudinal sections of Lupin Mine, west zone and central zone, and the stress determination sites are shown in Figures 3 and 4, respectively.

Shaft deepening is presently in progress with the final phase to reach a depth of 1184 m. The mine openings are also accessed with a ramp to a depth of 910 m to date.

GROUND STRESS DETERMINATIONS

Ground stress determinations were carried out by overcoring strain relief technique using CSIR triaxial strain cells. Details of testing procedures and instrument specifications are given in the references (2,3).

Measurements were taken in the west zone of the mine in the hanging

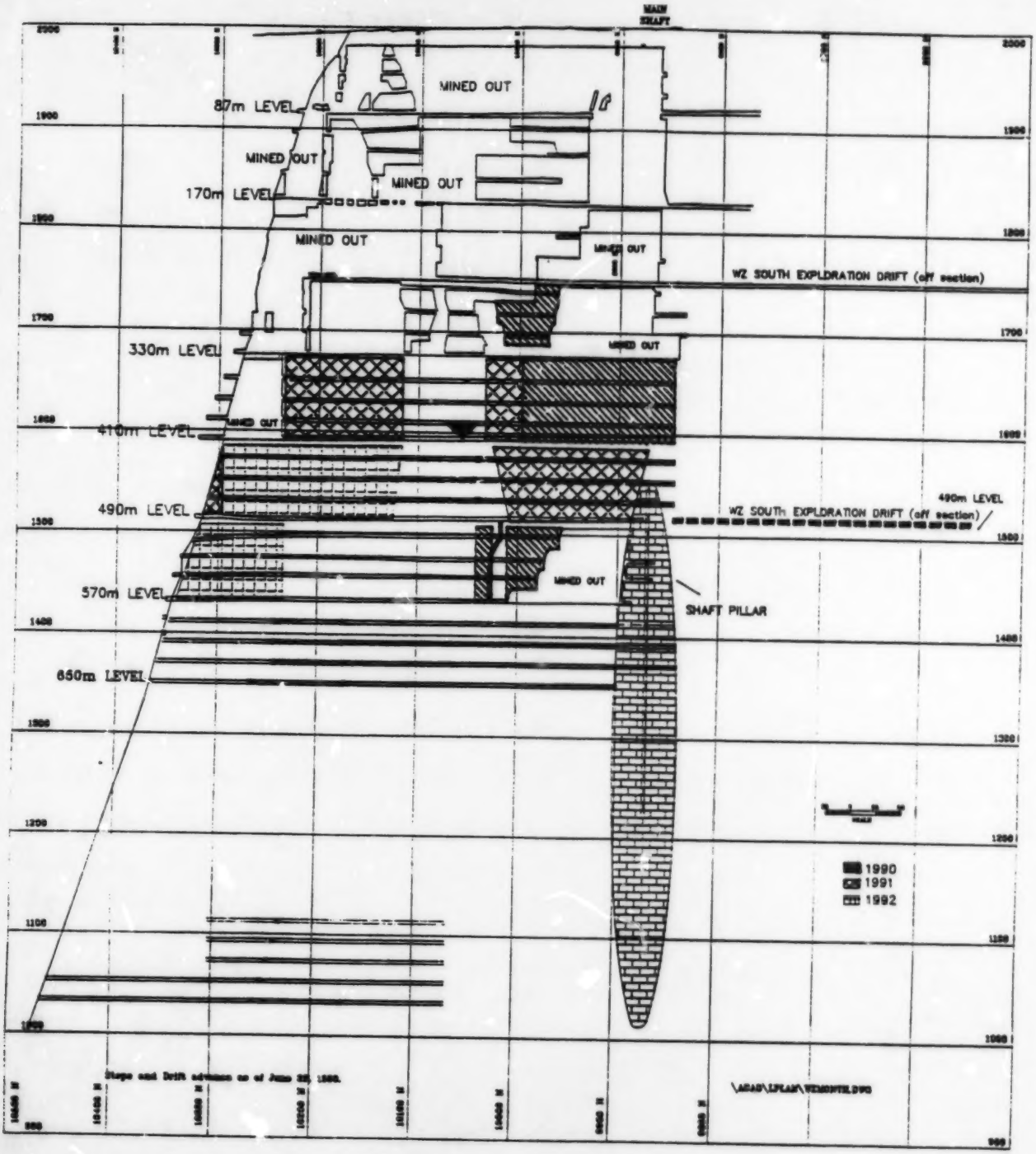

Fig. 3 - Longitudinal section of Lupin Mine, west zone, (▼) stress determination sites 410 level.

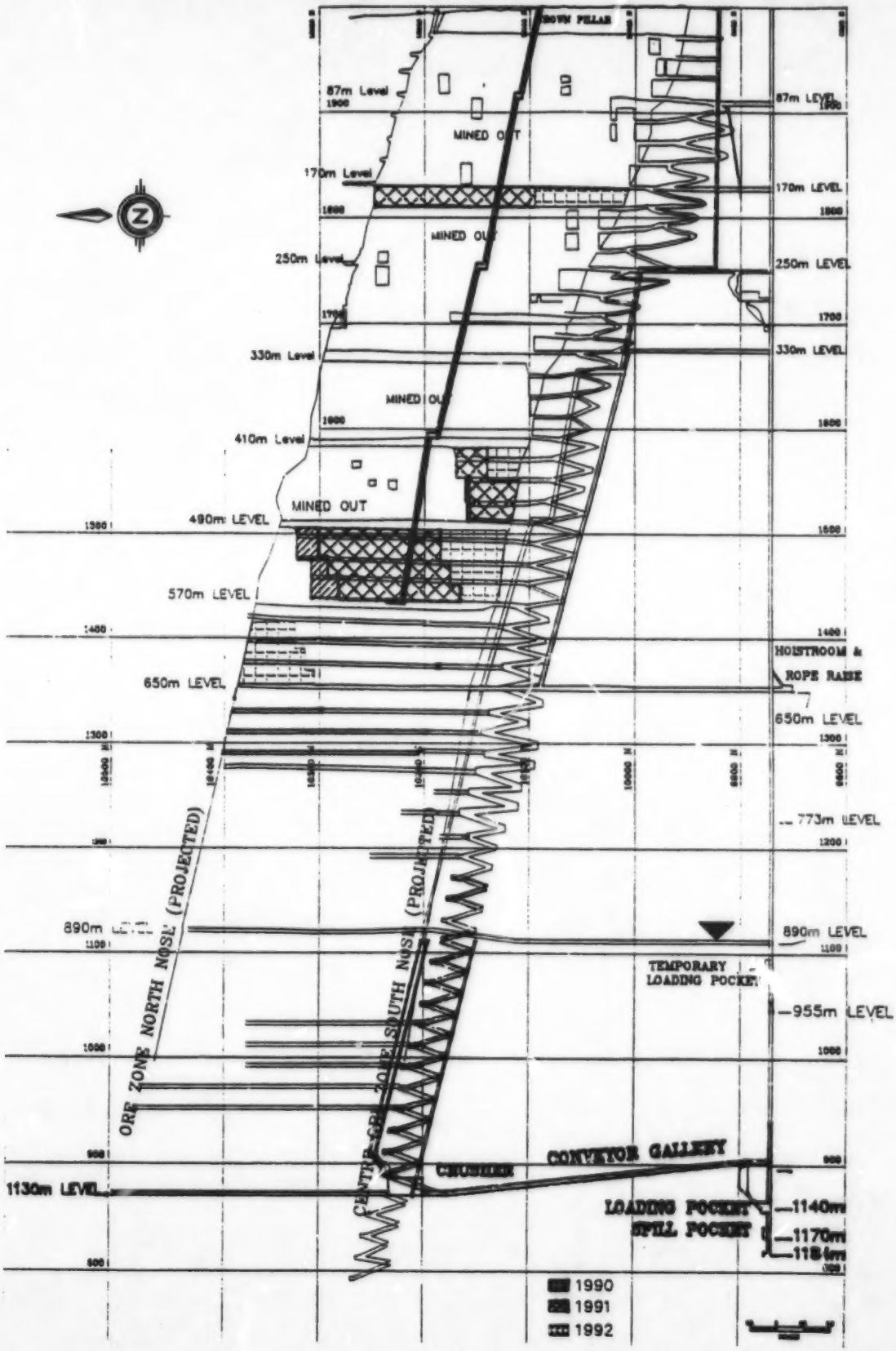

Fig. 4 - Longitudinal section of Lupin Mine, centre zone, (v) stress determination site 890 level.

wall, footwall and orebody on the 410 level, and in the hanging wall on the 890 level. The location and orientation of stress determination holes are shown in Figures 5 and 6. Test holes intersected fine grained phyllite, greywacke/quartzite in the hanging wall and footwall strata and a coarse massive sulphide rock (iron formation) in the orebody.

On the 410 level, test holes in the hanging wall and footwall were drilled perpendicular and in the orebody parallel to the main structural trend and foliation plan. All overcoring tests in the footwall (EBL 410-FW1) and orebody (EBL 410-OB1, EBL 410-OB2) were successful. In the hanging wall, because of core breakage, out of five tests attempted only two overcoring tests (EBL 410-HW1, EBL 410-HW5) were successful. On the 890 level, a test hole was drilled along the strike of foliated phyllite/siliceous phyllite. Two overcoring measurements (EBL 890-HW1, EBL 890-HW2) were taken. One successfully installed overcored test (EBL 890-HW3) broke off at the cell centre location by core retrieval. The depths of overcoring tests and the strain recovery from triaxial measurements are given in Table 1.

At the stress determination sites the ambient underground temperature was $+4^{o}C$ with 85% relative humidity on the 410 level and $+10^{o}C$ with 90% relative humidity on the 890 level. Successful bonding of strain cells in the EX-pilot holes was achieved using two component gauge adhesive cements (Versilok HI-406 and Hoettinger X60). Prior to the installation of strain cells, the EX-pilot hole was cleaned and dried several times using alcohol and generous amounts of acetone. The adhesive cement mixture having a pot life of 3-5 minutes, cured after 15-20 minutes. Overcoring commenced in about one hour after the strain cells were installed.

An air driven drill machine of type VAG (standard head with screw fit), capable of drilling a 99.06 mm diameter hole to the required depth, was used. For overcoring, a core barrel bit was used which yielded a core diameter of 83.8 mm. Prior to overcoring the hole was drilled with a diamond bit yielding

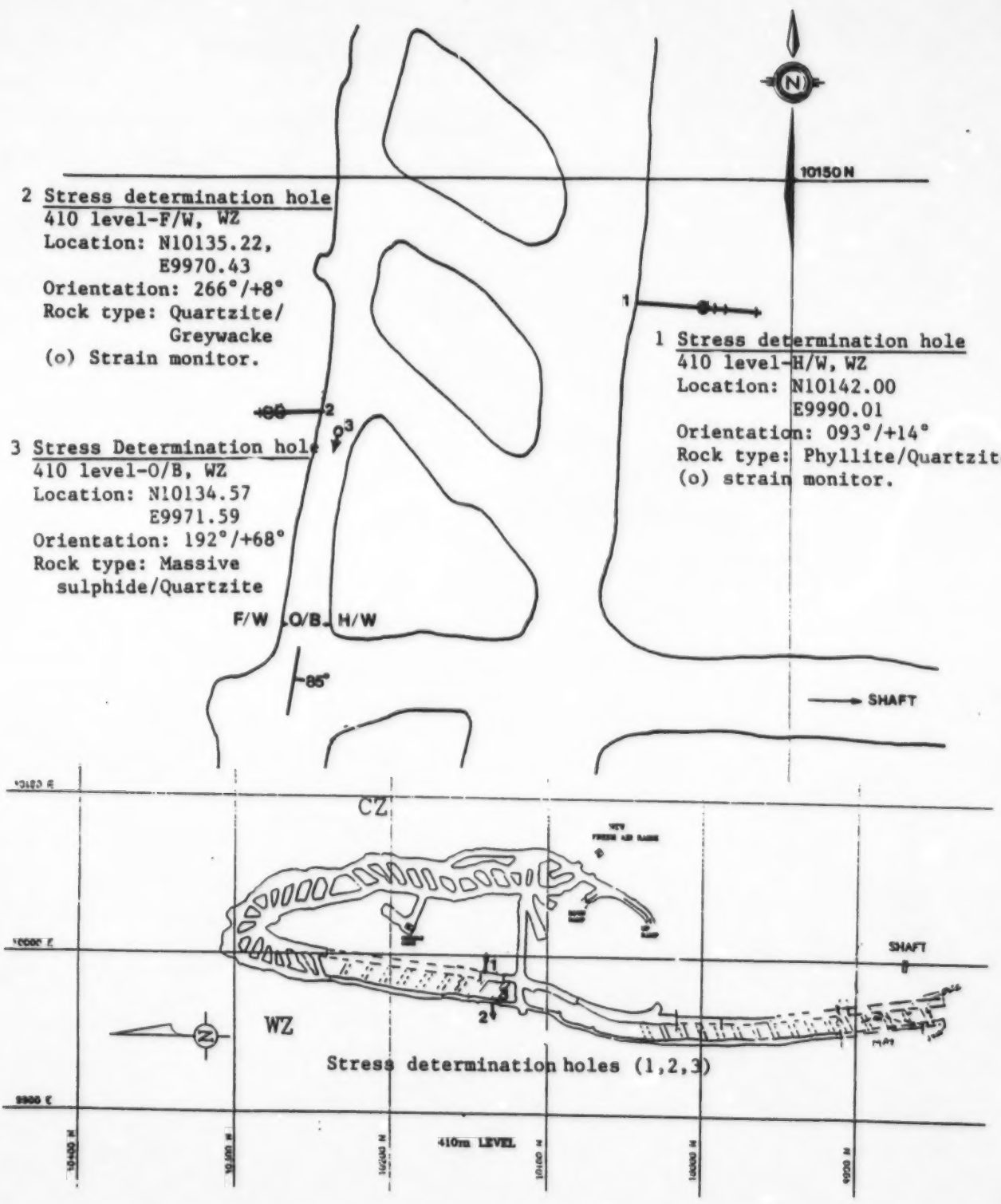

Fig. 5 - Stress determination sites 410 level (not to scale).

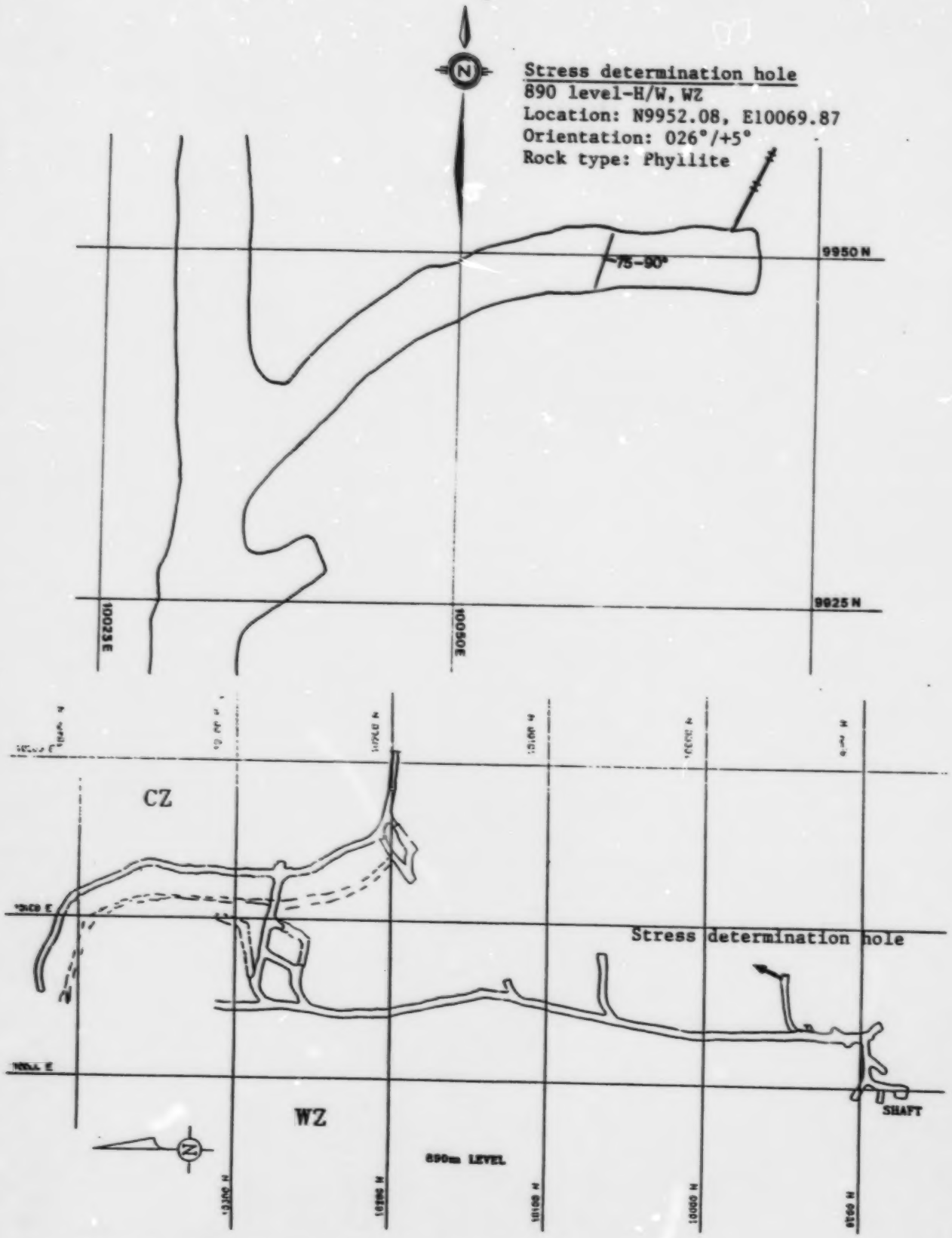

Fig. 6 - Stress determination site 890 level (not to scale).

Table 1 - Elastic strain recovery from overcoring measurements

Location	Test No.	Depth	Elastic Strain Recovery (με)												SI(*) Rosette:		
			Gauge No:														
		(m)	1	2	3	4	5	6	7	8	9	10	11	12	A	B	C
410 level H/W	EBL 410-HW1	3.84	140	155	145	150	345	325	180	205	550	290	160	425	20	5	5
	EBL 410-HW5	7.70	275	305	15	-20	395	305	115	215	715	105	70	665	5	10	15
410 level F/W	EBL 410-FW1	4.00	375	380	330	335	600	605	295	275	475	320	300	465	10	15	10
410 level O/B	EBL 410-OB1	3.65	255	325	160	120	635	550	185	320	300	230	160	180	30	50	50
	EBL 410-OB2	4.30	250	180	110	150	585	500	135	270	207	275	110	70	30	50	28
890 level H/W	EBL 890-HW1	4.00	555	425	490	610	760	375	440	840	740	845	360	250	5	15	5
	EBL 890-HW2	4.60	540	480	460	530	720	410	320	640	630	675	430	385	10	10	0

Note: Overcoring tests not successful: EBL 410-HW2, EBL 410-HW3, EBL 410-HW4, EBL 890-HW3.

(*) Strain invariance: sum of strain in two orthogonal directions, $\varepsilon_1 + \varepsilon_3 = \varepsilon_2 + \varepsilon_4$.

Total depth of overcoring test holes:
410 level-H/W - 8.00 m
410 level-F/W - 4.20 m
410 level-O/B - 4.50 m
890 level-H/W - 4.80 m

core of 72.5 mm diameter.

LABORATORY TESTING

The intact core specimens from stress determination holes were tested in the laboratory. Results from compression tests to obtain the elastic constants and uniaxial compressive strengths are summarized in Table 2. A total of 17 specimens were prepared and strain gauged following the standard testing procedure (4,5). Solid cores (diameter - 72.5 mm) and overcore specimens (diameter - 83.8 mm) with an EX centre hole having a height to diameter ratio 2.3 to 3.0 were loaded uniaxially. Elastic moduli and Poisson's ratios were calculated at about 50% of ultimate strength. Uniaxial compressive strengths were determined using a 200 ton press.

In addition, tests were carried out on 23 mm diameter core samples obtained from EX-holes in overcoring measurement sites. A total of 107 Point Load tests were made using the BEMEK portable rock testing unit. The rock testing unit computes uniaxial compressive strength values from the Point Load Index. The results are summarized in Table 3. The values for compressive strength from Point Load tests were in the range of 70-100 MPa for phyllite/siliceous phyllite, 107-190 MPa for quartzite/metagreywacke, and 194-252 MPa for massive sulphide (orebody).

STRESS DETERMINATION RESULTS

The results of stress tensor analyses from overcoring strain recovery measurements are given in Table 4. The stress components and the direction of principal compressive stresses are related to the mine coordinate system (Mine grid north is 29° west of True north). The orientations of the principal compressive stresses are illustrated in an equal area net, lower hemisphere projection in Figure 7.

The stress determinations show that for individual sites, generally,

Table 2 - Determination of Elastic Modulus (E), Poisson's Ratio (r), and Uniaxial Compressive Strength (UCS) from compression tests.

Location	Rock Type	Core Specimen Test No.	Hgt. (mm)	Dia. (mm)	Ratio H/D	E (GPa)	v	UCS (MPa)	Remarks	Load (+)
410 level H/W	Phyllite/ Quartzite	EBL 410-HW1	210	83.8	3.0	63.8*	0.17*		Overcore test	⊥
	"	EBL 410-HW2	183	72.5	2.5	65.5	0.15		--	"
	"	EBL 410-HW3	183	72.5	2.5	66.4	0.25		--	"
	"	EBL 410-HW4	176	72.5	2.4	59.0	0.15		--	"
	"	EBL 410-HW5	205	83.8	2.4	62.0*	0.18*		Overcore test	"
410 level F/W	Quartzite (Amph. rich)	EBL 410-FW1	220	83.8	2.6	69.3*	0.13*		Overcore test	"
410 level O/B	Massive sulphide (siliceous)	EBL 410-OB1	195	88.8	2.3	72.2*	0.22*		Overcore test	⊥
		EBL 410-OB2	193	83.8	2.3	89.6*	0.20*		Overcore test	"
		EBL 410-OB3	182	72.5	2.5	100.0	0.19		--	"
	"	EBL 410-OB4	181	72.5	2.5	104.6	0.21		--	"
		EBL 410-OB5	182	72.5	2.5	90.9	0.11		--	"
890 level H/W	Phyllite (siliceous)	EBL 890-HW1	200	83.8	2.4	56.9*	0.27*		Overcore test	"
		EBL 890-HW2	210	83.8	2.5	61.5*	0.28*		Overcore test	"
	"	EBL 890-HW3	195	83.8	2.3	50.1	0.29		--	"
	"	EBL 890-HW4	184	72.5	2.5	48.3	0.32		--	"
	"	EBL 890 HW5	183	72.5	2.5	48.8	0.28		--	"
	"	EBL 890-HW6	183	72.5	2.5	46.6	0.26		--	"

* Elastic constants (E and r) used for stress tensor analysis.

(+) Core specimen loaded perpendicular (⊥) or parallel (∥) to the bedding plane or foliation in uniaxial compression test.

Table 3 - Determination of uniaxial compressive strength (UCS) from Point Load Tests.

Rock Type	Location	No. of Tests	UCS (MPa)
Phyllite	410L-H/W	16	82.0±13.8
"	410L-F/W	10	84.7±15.5
"	890L-H/W	18	86.4±10.2
Quartzite	410L-H/W	12	130.0±23.1
"	410L-F/W	19	155.4±33.1
"	890L-H/W	12	130.2±12.6
Massive sulphide	410L-O/B	20	223.1±29.5

Note: Core specimens (Dia. = 23 mm) loaded with an oblique angle and/or parallel to foliation or bedding plane.

Table 4 - Stress components, magnitude and orientation of the principal stresses from overcoring measurements Lupin Mine, Northwest Territories.

Location (*)	Test No.	Stress Components (MPa) (Standard errors in brackets) σEW	σNS	σV	τEN	τNV	τVE	Std. Dev.	Principal Stresses (MPa) Mag./Dip σ1	σ2	σ3
410 level H/W	EBL 410-HW1	14.60	15.50	9.20	2.50	-1.40	1.20	0.07	17.60	13.40	8.40
		(0.2)	(0.4)	(0.2)	(0.2)	(0.2)	(0.1)		010/02	279/23	105/66
	EBL 410-HW5	12.60	17.80	9.5	5.8	-1.20	-4.9	0.29	22.70	12.00	5.20
		(0.8)	(1.3)	(0.8)	(0.6)	(0.6)	(0.4)		008/16	112/40	260/45
410 level F/W	EBL 410-FW1	25.30	20.30	17.00	4.40	-1.90	-1.60	0.28	28.40	18.40	16.30
		(0.8)	(1.4)	(0.8)	(0.7)	(0.7)	(0.5)		029/12	294/20	149/38
410 level O/B	EBL 410-OB1	21.80	15.00	19.60	2.30	-3.20	2.60	0.58	23.50	20.70	12.30
		(1.9)	(3.2)	(1.9)	(1.5)	(1.5)	(1.1)		239/33	008/44	129/28
	EBL 410-OB2	21.90	12.00	19.10	3.0	0.10	2.30	0.55	23.90	18.20	11.10
		(2.2)	(3.5)	(2.2)	(1.7)	(1.7)	(1.2)		226/26	036/64	134/03
890 level H/W	EBL 890-HW1	33.80	29.80	23.30	8.60	2.80	1.50	0.31	41.00	24.10	21.70
		(0.8)	(1.3)	(0.8)	(0.6)	(0.6)	(0.5)		202/09	103/42	302/47
	EBL 890-HW2	31.30	33.30	23.90	7.20	1.80	0.60	0.33	39.80	25.30	23.40
		(0.9)	(1.5)	(0.9)	(0.7)	(0.7)	(0.5)		191/06	099/23	296/65

Note: Stress components and the principal stresses orientation (Bearing/Dip in degrees) related to True North.

(*) Depth below surface in metres (410 m and 890 m).

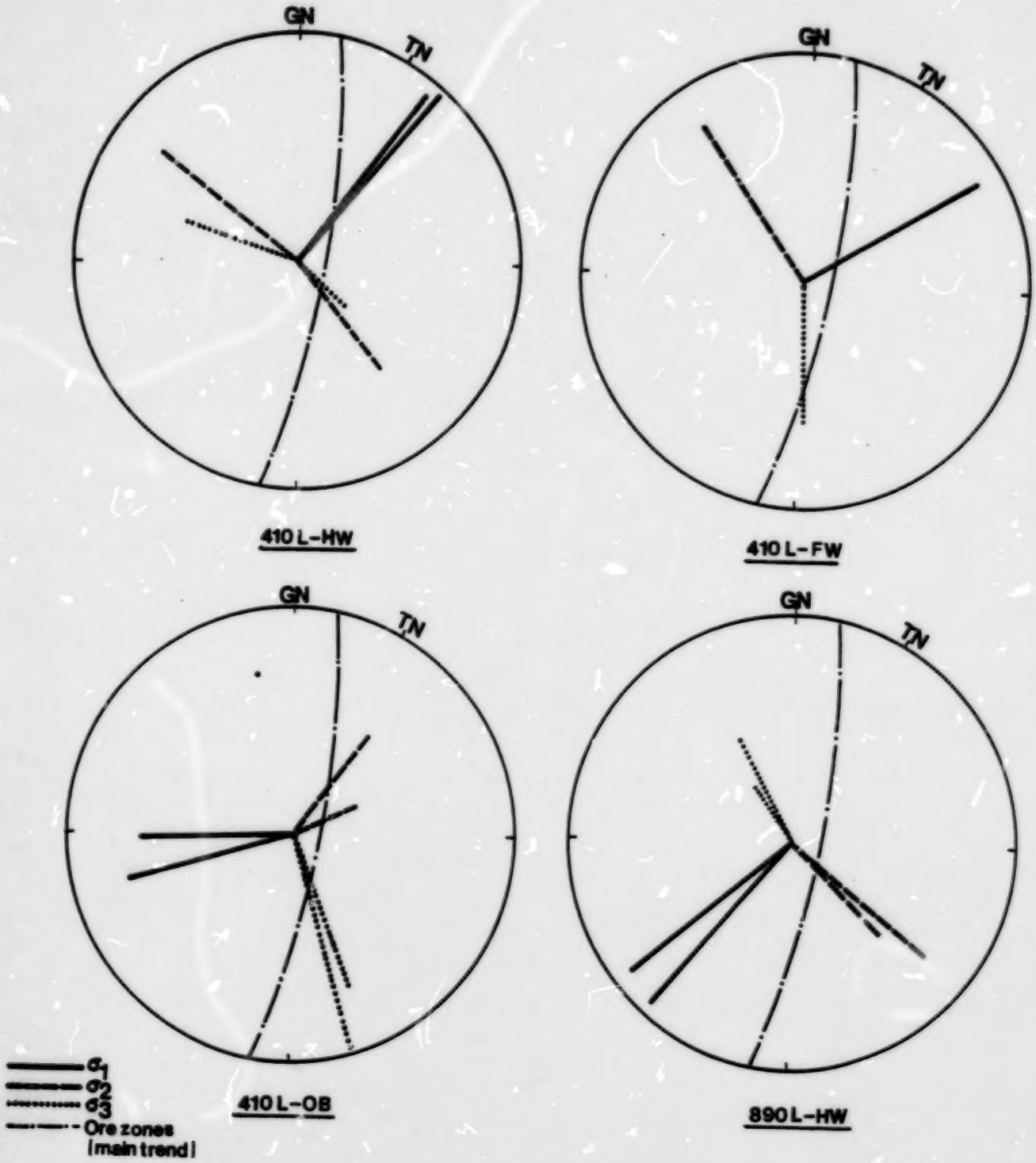

Fig. 7 - Orientation of the principal compressive stresses and main trend or ore zones from Mine grid north (= 29° west of True north) in an equal area net, lower hemisphere projection.

good agreement exists between the magnitudes and orientations of the principal compressive stresses. The orientation of maximum and intermediate principal stresses on the 410 level hanging wall/footwall are comparable with 890 level hanging wall. The maximum principal stress shows a horizontal NE/SW trend with a mean azimuth and dip of $45^{o}/09^{o}$. Analysis of structural data from 490 level indicated a similar trend (6). The intermediate principal stress is sub-horizontal with a mean azimuth and dip of $315^{o}/30^{o}$. The minimum principal stress is sub-vertical with varying direction.

On the 410 level orebody, however, the maximum principal stress is WSW/sub-horizontal. This indicates a clockwise rotation by about 37^{o} from the main NE/SW trend. The intermediate principal stress is near vertical while the minimum principal stress shows a horizontal to sub-horizontal SSE direction.

The comparison of stress magnitudes suggests that on the 410 level, the sum of principal stresses in the footwall are about 35% and in the orebody 27% higher than the values determined in the hanging wall. The measured vertical stress components in the hanging wall on the 410 and 890 levels approached the estimated average overburden weight of 0.0285 MN/m^3 x depth (m) in MPa. However, in the footwall and orebody on the 410 level, the measured vertical stresses were up to 40% higher than the estimated average overburden weight. The effects of test locations and the increase in the density of the overburden rock (orebody) possibly resulted in excessive values of vertical stresses.

The maximum principal stress is oriented with an angle varying between 40^{o} to 70^{o} to the main trend of steeply dipping ore zones and structural features. The angular relationship between the principal stresses and the ore zones are illustrated in Figure 7.

The variation of the sum of principal stresses and the stress ratios at the stress determination sites are given in Table 5. The results indicate a

relatively linear increase of ground stresses with depth, with varying ratios of maximum to intermediate (σ_1/σ_2) as well as maximum, intermediate principal stresses to vertical stress (σ_1/σ_v, σ_2/σ_v).

Evaluation of stress magnitudes resulted in the average stress gradients for the hanging wall, footwall and orebody as follows:

Location	Stress Gradients (MPa/m)			
	σ_1	σ_2	σ_3	σ_v
Hanging wall	0.0472	0.0293	0.0210	0.0247
Footwall	0.0693	0.0448	0.0397	0.0443
Orebody	0.0578	0.0473	0.0285	0.0443

Figure 8 shows the increase of the sum of principal stresses, maximum, intermediate principal stresses and the vertical stress as a function of depth from the underground stress determinations in the Canadian Shield (7). The average stress gradients from Lupin Mine are also plotted in Figure 8. A comparison suggests the present stress data follow the trend established in the Canadian Shield. Data plots, however, indicate that the values from the Lupin Mine are confined to the average and/or lower range of the referenced data and no extreme gradients were determined at the mine site.

GROUND MOVEMENT MONITORING

As a part of the proposed rock mechanics instrumentation for stability evaluations, CANMET strain monitors (8) were installed in stress determination holes on the 410 level. The footwall hole was fitted with two strain monitors to measure deformation in vertical and horizontal directions, and in the hanging wall hole only one monitor was installed in a vertical position. The monitors were connected to a data logger at each site for continuous recording of strain changes. Their record will provide the basis for the analysis of

Table 5 - Sum of principal stresses and stress ratios on the 410 and 810 levels

Location	$\sigma_1+\sigma_2+\sigma_3$ (MPa)	σ_1/σ_2	σ_1/σ_v	σ_2/σ_v	$\frac{2\,\sigma_1}{\sigma_2+\sigma_3}$
410 level	39.40	1.31	1.91	1.45	1.61
H/W	39.90	1.89	2.39	1.26	2.64
410 level	63.10	1.54	1.67	1.08	1.64
F/W					
410 level	56.50	1.13	1.20	1.05	1.42
O/B	53.10	1.32	1.25	0.95	1.63
890 level	86.80	1.70	1.76	1.03	1.80
H/W	88.50	1.57	1.66	1.06	1.63

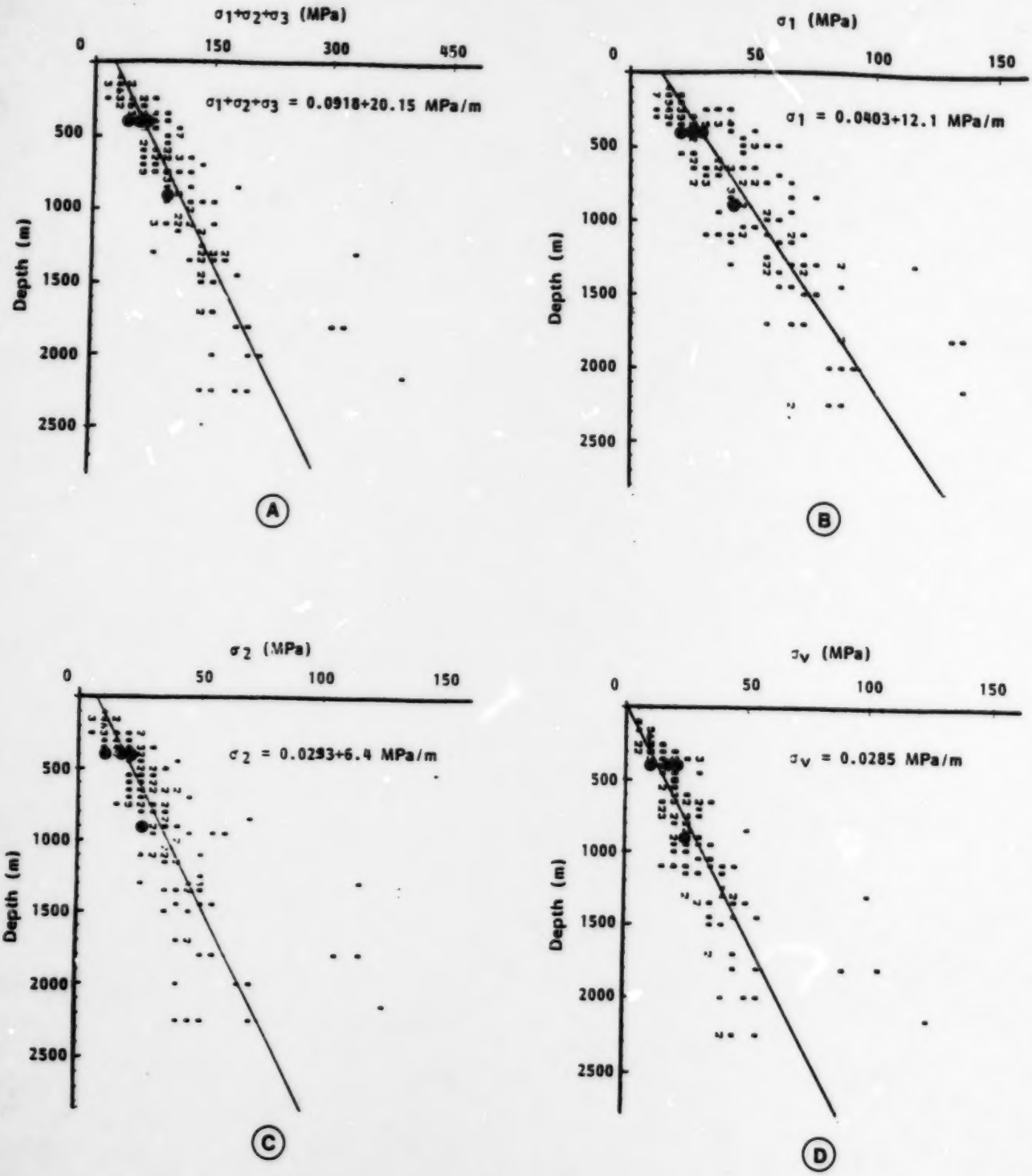

Fig. 8 - Increase of sum of principal stresses (A), maximum and intermediate principal stresses (B,C), and vertical stress components (D) with depth in the Canadian Shield (7). (●) Average stress values Lupin Mine site.

mining induced stresses.

The locations of strain monitors are shown in Figure 5 and the installation data are given in Table 6. Calibration curves for monitors are reproduced in Figure 9. Figure 10 and 11 show the strain monitoring system.

CONCLUSIONS

The orientation of principal compressive stresses and average stress gradients determined at the Lupin Mine site are comparable with the data obtained from underground hard rock mines in the Canadian Shield. In a mine scale, because of structural setting and variations in rock strength, it appears that the stress distribution in the hanging wall, footwall and orebody is not unique. It is, therefore, recommended that caution be exercised when extrapolating the present stress values to different sites and levels of the mine.

ACKNOWLEDGEMENTS

The cooperation of the staff at Echo Bay Mines Ltd., Lupin Operation, is very much appreciated, especially that of B. Skeeles, ground control engineer, who provided essential assistance during the field work. S. Vongpaisal, CANMET, acted as liason officer on this project.

Table 6 - Location data and calibration factors for strain monitors

Location	Installation Date	Borehole Orientation *	Strain Monitor No.	Depth from Collar (m)	Orientation	Frequency (Hz) Initial	Frequency (Hz) Installed	Calibration Factor (10^{-4} mm/Hz)
410 level H/W	18/07/90	093°/+14°	HNM-22B	4.72	Vertical	1165	1522	4.00
410 level F/W	21/07/90	266°/+08°	HNM-23	3.96	Vertical	1269	2324	3.90
	21/07/90	266°/+08°	HNM-25	3.60	Horizontal	1193	1625	4.00

(*) Diamond drill hole diameter = 99.06 mm.

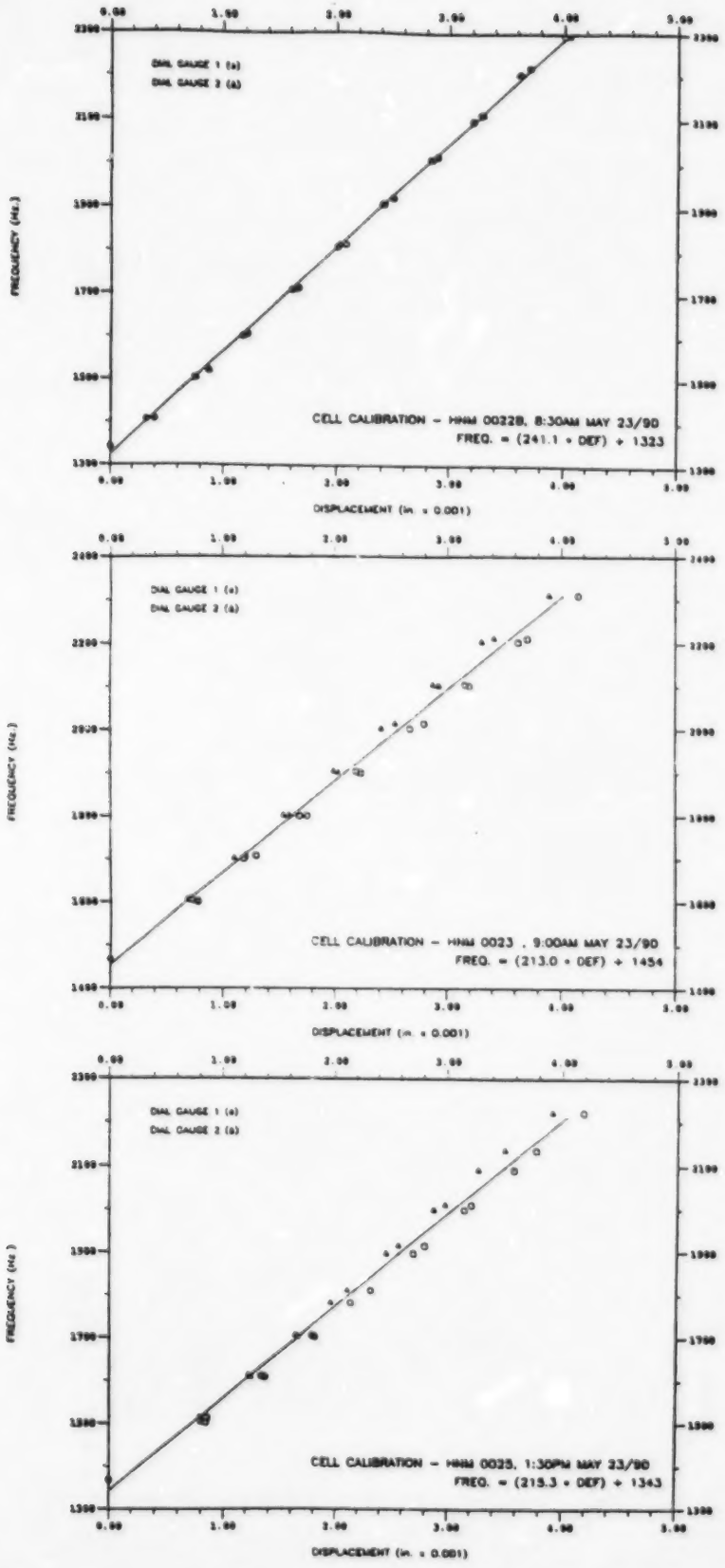
DIAL GAUGE 1 (a)
DIAL GAUGE 2 (a)
CELL CALIBRATION – HNM 0022B, 8:30AM MAY 23/90
FREQ. = (241.1 • DEF) + 1323
FREQUENCY (Hz.)
DISPLACEMENT (in. x 0.001)
DIAL GAUGE 1 (a)
DIAL GAUGE 2 (a)
CELL CALIBRATION – HNM 0023 , 9:00AM MAY 23/90
FREQ. = (213.0 • DEF) + 1454
FREQUENCY (Hz.)
DISPLACEMENT (in. x 0.001)
DIAL GAUGE 1 (a)
DIAL GAUGE 2 (a)
CELL CALIBRATION – HNM 0025, 1:30PM MAY 23/90
FREQ. = (215.3 • DEF) + 1343
FREQUENCY (Hz.)
DISPLACEMENT (in. x 0.001)

Fig. 9 - Calibration curves for strain monitors HNM-22B, HNM-23 and HNM-25.

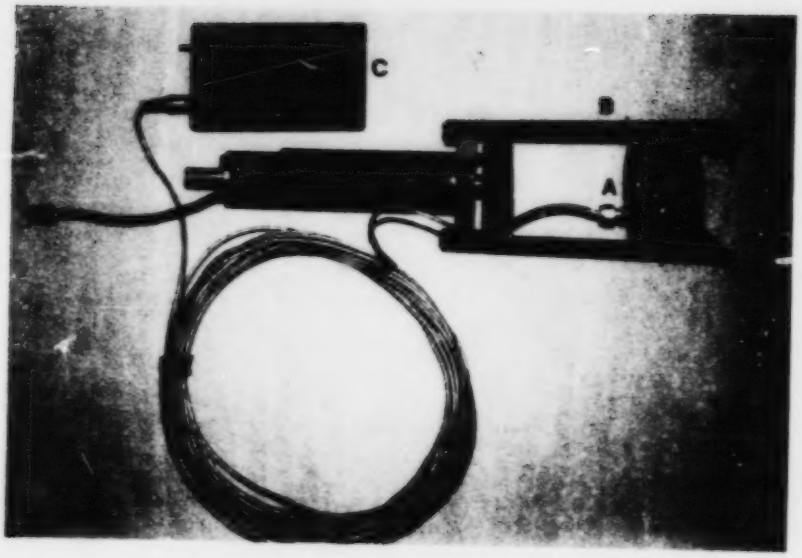

Fig. 10 - CANMET strain monitoring system, (A) strain monitor, (B) installing tool, (C) readout unit.

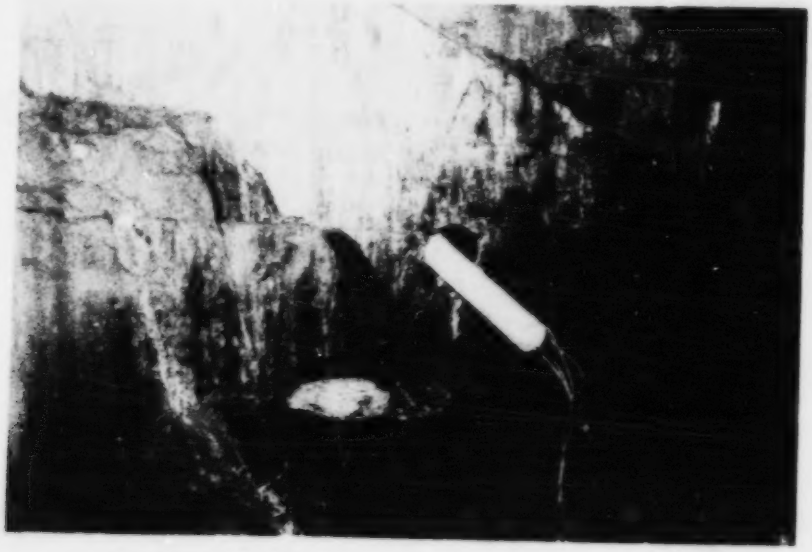

Fig. 11 - Data logger for continuous strain monitoring, 410 level hanging wall.

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